Master's Thesis of Engineering

Manufacturing and Evaluation of Soft Morphing Flow Separator of Car

자동차용 소프트 모핑 유동박리장치의

제조 및 평가

August 2017

Graduate School of Seoul National University

College of Engineering

Department of Mechanical & Aerospace Engineering

Anna Iakovleva

Manufacturing and Evaluation of Soft Morphing Flow Separator of Car

Academic advisor Prof. Sung-Hoon Ahn

Submitting a Master's Thesis of Engineering

May 2017

Graduate School of Seoul National University

College of Engineering

Department of Mechanical & Aerospace Engineering

Anna Iakovleva

Confirming the Master's Thesis written by

Anna Iakovleva

June 2017

Chair ______ Kunwoo Lee ______ (Seal)

Vice Chair ______ Sung-Hoon Ahn ______ (Seal)

Examiner ______ Suk Won Cha ______ (Seal)

Abstract

Manufacturing and Evaluation of Soft Morphing Flow Separator of Car

Anna Iakovleva

Department of Mechanical and Aerospace Engineering

The Graduate School

Seoul National University

An interest in morphing technologies has steadily increased over the past few decades in many areas including aircraft and automotive industry. Such technologies are considered to be promising for improving functioning and effectiveness of vehicles over a broad range of working conditions. Particularly, in land vehicles morphing structures can be used for replacing their aerodynamic pieces for transforming their surfaces without opening gaps and discrete sections which cause aerodynamic losses and other drawbacks such as noise, vibration and harshness (NVH), also known as noise and vibration (N&V) characteristics of vehicles. In the proposed work, a smart soft composite actuator based on shape memory alloy (SMA) wires was developed for fabrication of an air flow separator installed in the rear part of a 1/8-scaled radio-controlled car. For evaluation of the aerodynamic performance and efficiency of the car, field tests were conducted, and the results were then compared with the performance of the car without the flow separator tested under the same conditions.

Keywords: Smart materials, shape memory alloy (SMA), smart soft composite (SSC), morphing structure, car flow separator.

***Student Number**: 2015-23294*

Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1 Overview

While driving a car at a high speed, a turbulent air pocket appears behind it. When moving, the car is passing through the air which goes over its surface and some of the air goes underneath [9] resulting in excessive pressure under the bottom of the car (Fig. 1). In turn, this effect leads to a decreased downforce and a rise of the vehicle, which significantly worsen performance and controllability of the vehicle. Aerodynamic body kits, such as spoilers and wings, have been developed to avoid this problem.

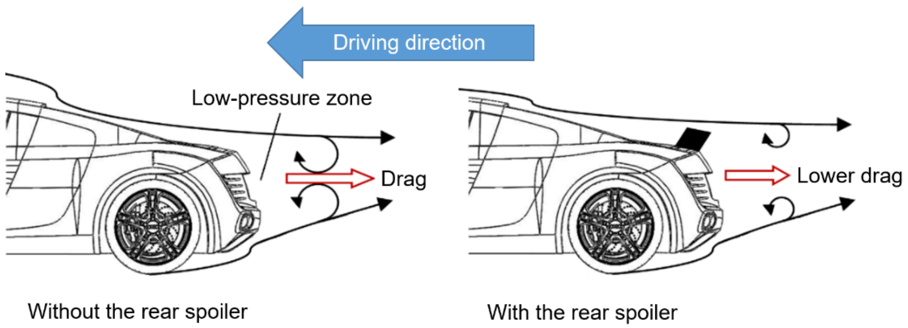


Figure 1. Illustration of the working principle of a rear spoiler

1.2 Purpose of research

Conventional hinged body kits consist of discrete sections. Consequently, such systems can have opening gaps in and between themselves and the main surface, which significantly increases aerodynamic losses. Furthermore, such components require additional mechanical parts that lead to increased weight and associated manufacturing costs of the car. Therefore, various approaches are being required to effectively solve aerodynamic problems on conventional systems.

This study is focused on developing a novel soft air flow separating system of car using smart materials, such as smart soft composite (SSC) and shape memory alloy (SMA). The separator was fabricated and then installed into the small size radio controlled car for aerodynamic performance evaluation.

Chapter 2 presents the materials that were used for manufacturing of the actuator, and chapter 3 is concentrated on the actuator design and its application as the car flow separator. Chapter 4 shows manufacturing process. Experimental data and performance evaluation method are presented in chapter 5. Finally, chapter 6 summarizes the results and highlights future plans.

Chapter 2. Materials

2.1 Shape memory alloy

Shape memory alloys (SMA) are materials having a shape memory effect and super elasticity, which highlights them among other conventional materials, such as plastics, metals, and traditional alloys. Over the past few decades, SMA have been extensively studied and applied in numerous areas, including robotics, biomedical field and automotive industry. In particular, they have attracted keen attention as promising candidates for use in sensors and actuators.

SMA is an alloy, which can remember and return to its original shape when heated [1]. This alloy exists in two different phases, which are dependent on temperature: a low temperature phase (martensite) and high temperature phase (austenite). At martensite phase, the crystal structure can be deformed to a desired shape due to low yield strength of SMA at this phase. Heating SMA above its phase transition temperature causes austenite phase, and SMA returns to its pre-deformed shape. In this phase, the crystal structure of SMA changes to a highly ordered structure and the atomic particles arrange symmetrically providing high yield strength at this phase [2].

Phase transformation of SMA is shown in Fig. 2.

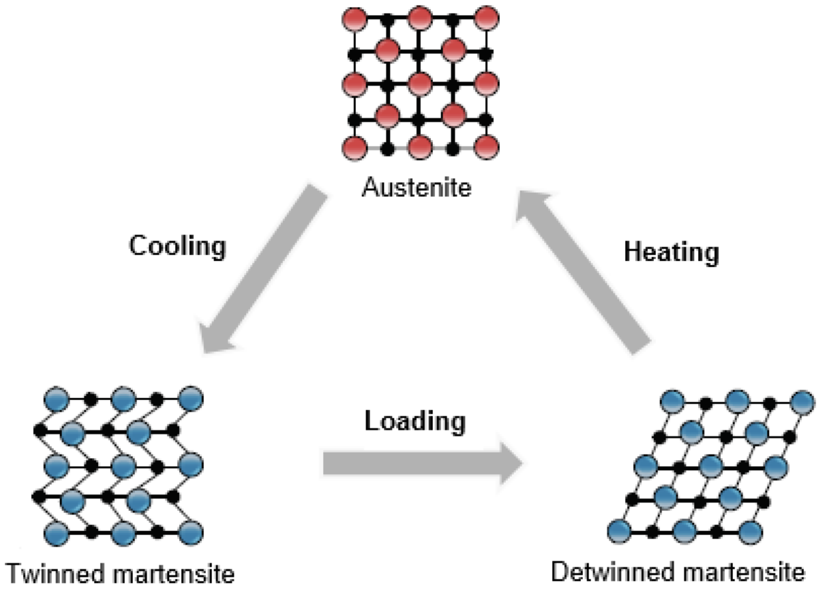


Figure 2. Phase transformation of SMA

SMA is available in different forms, including films, rods, tubes, and wires. The proposed work focuses on the application of SMA wire for design of the actuator. The wires used in this research are FLEXINOL® Actuator Wires, Dynalloy Inc., made of nickel-titanium and electrically driven. A diameter of the wires is 0.01 inches (254 μm) and an austenite start temperature is 68°C.

Table 1. Material properties of shape memory alloy (SMA)

Parameter	Description	Value
Young's modulus	Austenite (E_A) Martensite (E_M)	75 GPa 28 GPa
Phase transition temperature	Austenite start (T_{AS}) Austenite finish (T_{AF}) Martensite start (T_{MS}) Martensite finish (T_{MF})	68°C 78°C 52°C 42°C
Specific heat capacity	C	0.322J/g°C
Maximum deformation ratio	$\varepsilon_{ma\chi}$	8%

2.2 Ecoflex (Matrix)

Ecoflex® is an elastomeric rubber used as a matrix for the SSC actuator with embedded SMA wires. Cured rubber is soft, strong and “stretchy”, which provides good bending in the central area of the pattern while applying the electric current for actuating SMA.

Table 2. Material properties of Ecoflex®

Parameter	Value
Mixed viscosity	3,000 cps
Pot life	45 min.
Cure time	4 hours
Tensile strength	1.379 MPa
Elongation at break %	900%
Shrinkage (m/m)	< .001 m/m
Mix ratio	1A:1B by volume or weight
Useful temperature range	-53˚C to 232˚C
Dielectric strength	>13779.5 kV/m

2.3 PVC and ABS (Scaffolds)

Two types of materials were for fabrication of the actuator: acrylonitrile butadiene styrene (ABS plastic) and polyvinyl chloride (PVC) film. ABS scaffolds of 0.7 mm thickness fabricated by three-dimensional (3D) printing and then embedded within the top and bottom part of the actuator. They are used as the rigid supports to increase the stiffness.

Placing the SMA wires close to the upper boundary of the actuator for efficient bending requires additional support, which could protect the wires from coming out of the Ecoflex matrix after a number of working cycles. PVC film scaffolds processed by laser cutting was used for this purpose.

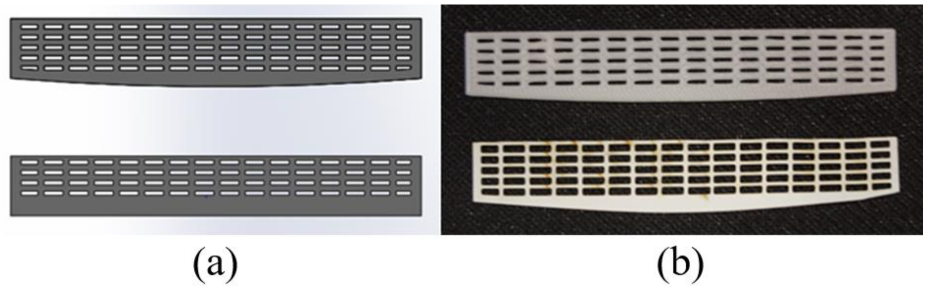


Figure 3. Scaffolds: (a) 3D models, (b) fabricated scaffolds for the upper side made of ABS plastic and PVC film

Chapter 3. Design

3.1 SMA based SSC actuator

The main function of the SMA based SSC actuator is separation of the airflow of the exterior surface of the car for improving its efficiency and performance on the road.

The designed actuator repeats the geometry of the rear part of the car and consists of Ecoflex matrix with embedded components: SMA wires and supporting scaffolds. Sixteen SMA wires, located at the same distance from each other, provides bending when actuated by an electric current. This concept is illustrated in Fig. 4.

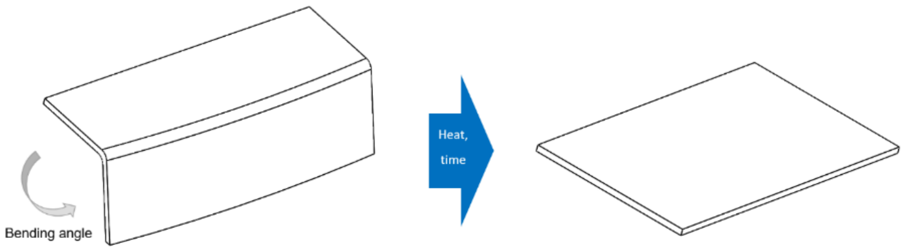


Figure 4. Bending concept of the SMA based SSC actuator

Two types of scaffolds (ABS and PVC) in the top and the bottom parts of sample used for increasing the stiffness and keeping the SMA wires inside the soft polymer matrix after number of cycles without its output of the base structure. The design of the actuator is shown in Fig. 5.

Fabricated lightweight structure is intended to replace conventional mechanical components in the rear part of the car and to prevent opening of gaps for reducing aerodynamic losses.

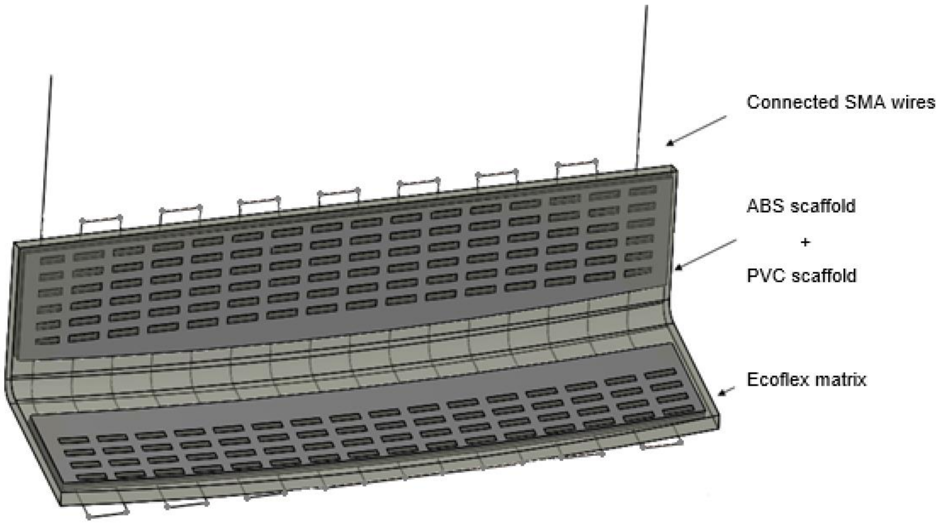


Figure 5. Design of the SMA based SSC actuator

3.2 Car flow separator

For installing the SSC actuator, the Kyosho Inferno GT2 Race Spec Audi R8 1:8 Scale Radio Controlled Nitro Race Car was used. The dimensions of the car are shown in Fig. 6.

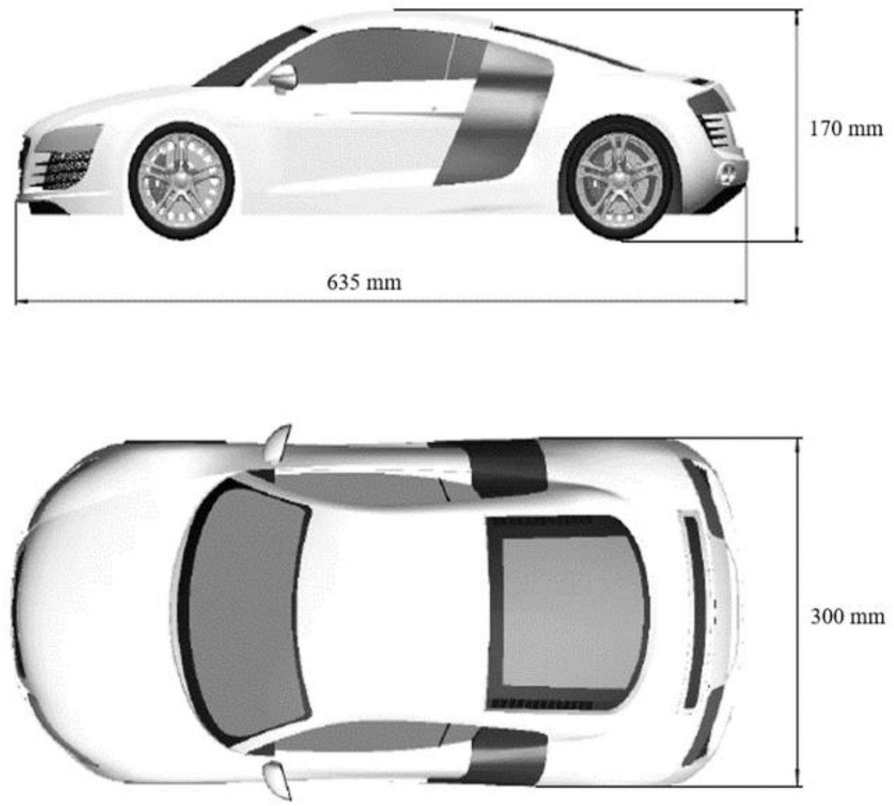


Figure 6. Dimensions of small-scale Audi R8 car

The SSC actuator was fixed on the 3D printed supporting frame made of ABS plastic (Fig. 7).

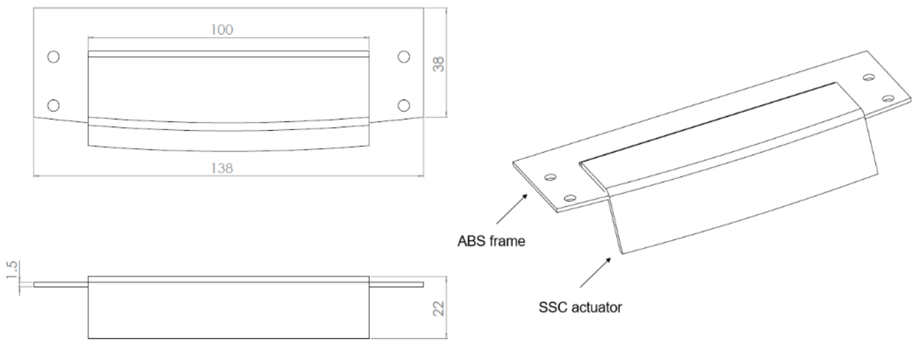


Figure 7. Assembly of the flow separator with the main dimensions

The assembly was then installed in the small-scale car by replacing the car boot and forming a flow separation mechanism shown in Fig. 8.

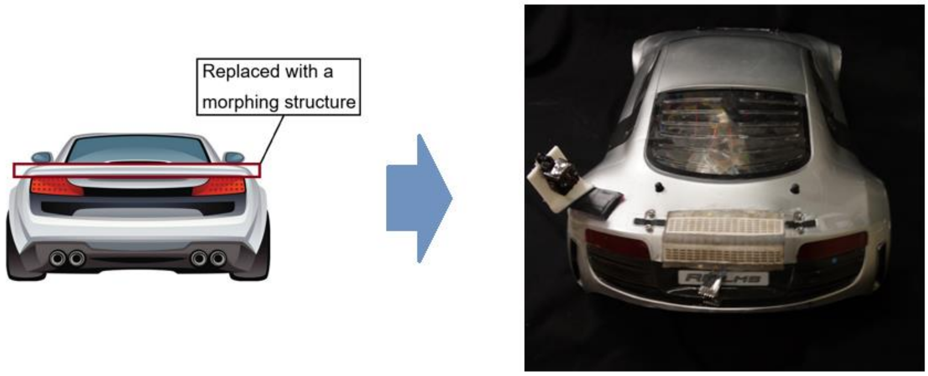


Figure 8. Schematic representation of the flow separator installation

Chapter 4. Manufacturing

4.1 SMA based SSC actuator

The SMA based SSC actuator was manufactured using PLA molds, SMA wires, PVC and ABS scaffolds, and polymer matrix (Ecoflex 00-30, Smoothon Inc.). Plastic molds (Fig. 9) and scaffolds were fabricated by "fused deposition manufacturing" (FDM) technology using 3D printer. The PVC scaffolds were processed by laser cutting of the PVC film.

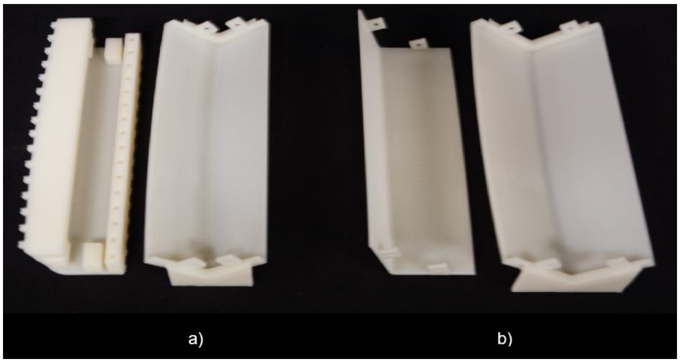


Figure 9. Fabrication molds for the SMA based SSC actuator: (a) first casting molds, (b) second casting molds

Manufacturing process of the actuator is divided into two steps of casting. The first step includes several operations: positioning of the SMA wires in the mold; combining of the mold components; injecting of the Ecoflex mixed at a 1A:1B ratio and curing at 55°C for 4 hours in an oven. After solidification of the polymer, the molds were separated, and the end-product of the first casting was obtained. The process is shown in Figure 10.

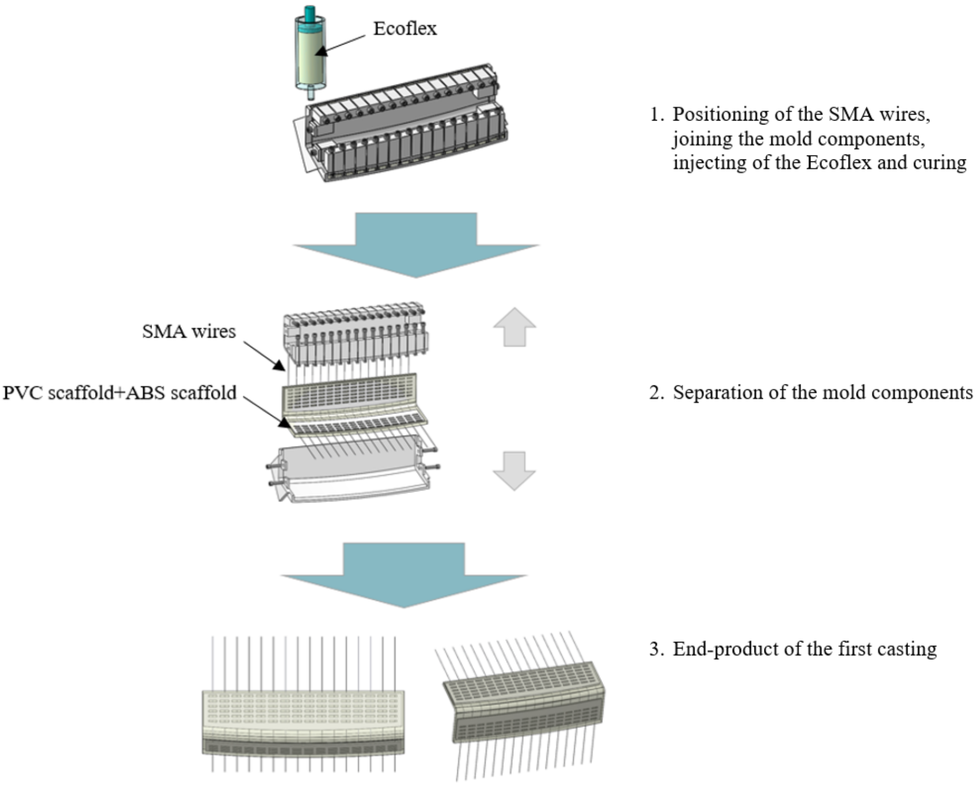


Figure 10. First casting of the SMA based SSC actuator

The second step of casting includes connecting of the SMA wires, placing the sample into the mold, and injection of the Ecoflex for covering the connection points of the wires and forming the edges of the actuator (Fig. 11), and curing for 4 hours at 55°C in the oven.

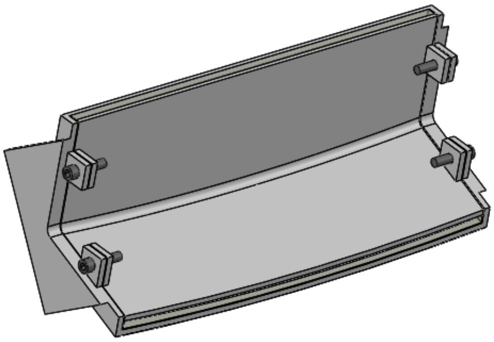


Figure 11. Second casting of the SMA based SSC actuator

After solidification process and mold separation, the finished sample was obtained. Fabricated actuator is shown in Fig. 12.

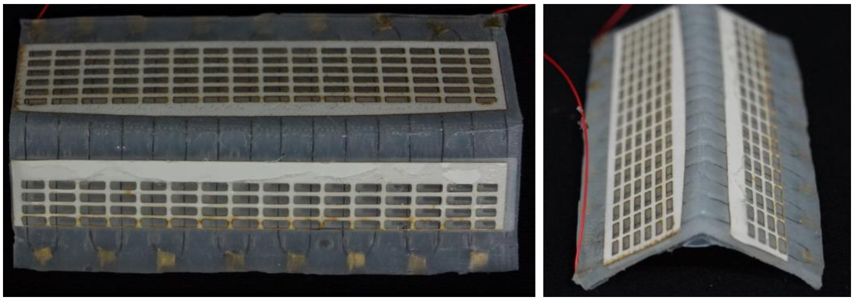


Figure 12. Fabricated actuator

4.2 Car flow separator

The air flow separator was fabricated by installing the SSC actuator on the 3D printed plastic frame, and then replacing the boot part of the small-size car with the obtained assembly (Fig. 13).

Figure 13. Installing SSC actuator into the car

Chapter 5. Experiment and results

5.1 SMA based SSC actuator performance evaluation

For evaluation of the SMA based SSC actuator bending performance, deformation test was conducted by fixing the sample to a support at room temperature, and then heating the actuator using electric current and cooling (Fig. 14).

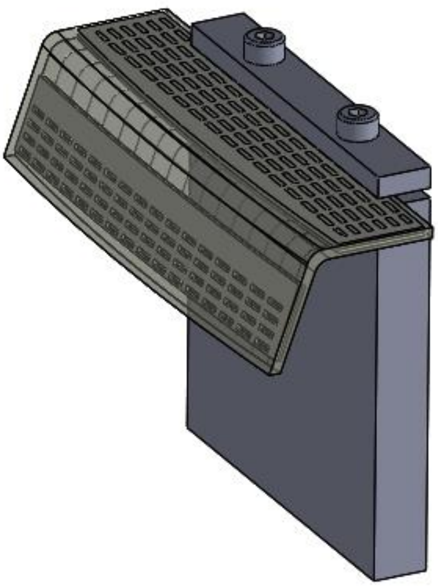


Figure 14. Experimental set-up

The bending deformation of the actuator is shown in Fig. 15.

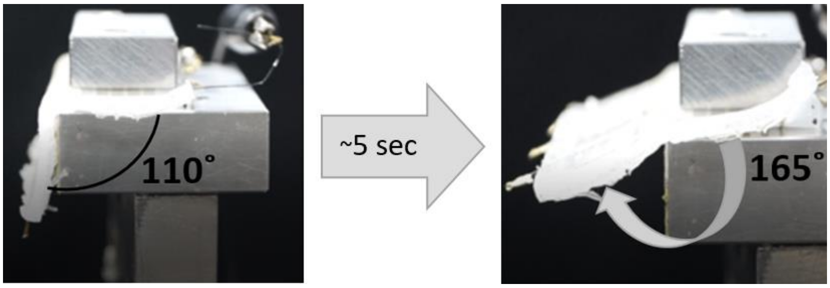


Figure 15. Maximum deformation of the SMA in the SSC actuator

5.2 Flow separator performance evaluation

The aerodynamic performance of the air flow separator was evaluated by conducting a field test. The electrical circuit (Fig. 16) was made for controlling the car movement and actuating the SSC actuator.

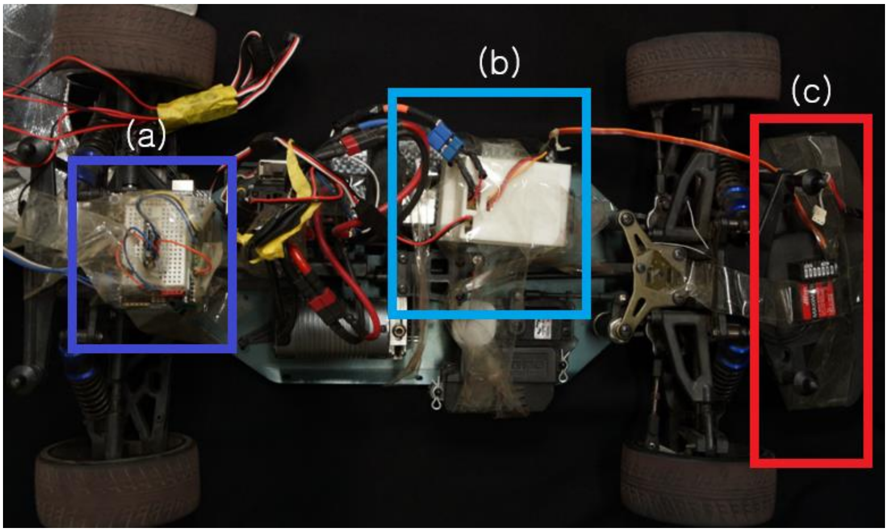


Figure 16. Electrical circuit for the small-size car: (a) pressure controller, (b) signal processing controller, (c) signal receiver

Along with the standard remote control for monitoring movement of the small-size car on the road, aircraft computer radio remote was programmed and used to control actuation of the flow separator. The miniature camera ("SQ8 mini 1080P full HD car DVR camera recorder") was used for capturing the actuating of the flow separator when moving the car at the high speed (Fig. 17).

(a) (b)

Figure 17. (a) Flash 8-8 Channel 2.4 GHz Aircraft Computer Radio; (b) SQ8 mini 1080P full HD car DVR camera recorder

The field test was conducted on a sport ground of the Seoul National University main campus (Fig. 18).

Figure 18. Field test area and the carpet

During the field test, two types of experiments were carried out: with the actuation of the SMA based SSC actuator in the flow separator, and with unactuated separator (Fig. 19). Images were captured by the mini camera installed on the back side of the car (Fig. 8).

(a) (b)

Figure 19. Two modes of the car: (a) with unactuated flow separator; (b) with actuated flow separator.

The results showing the changes in longitudinal acceleration (x-axis) and vertical acceleration (z-axis) in two cases are presented in Fig. 21.

The data for linear and vertical acceleration are obtained using the cell-phone application.

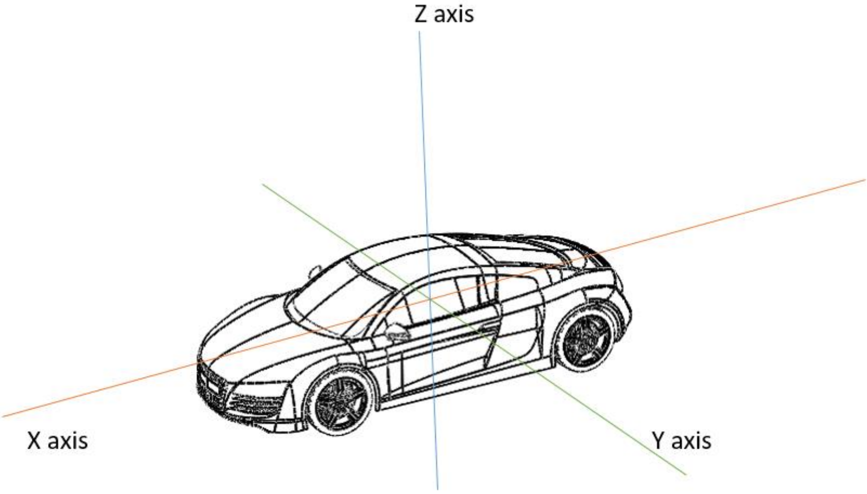
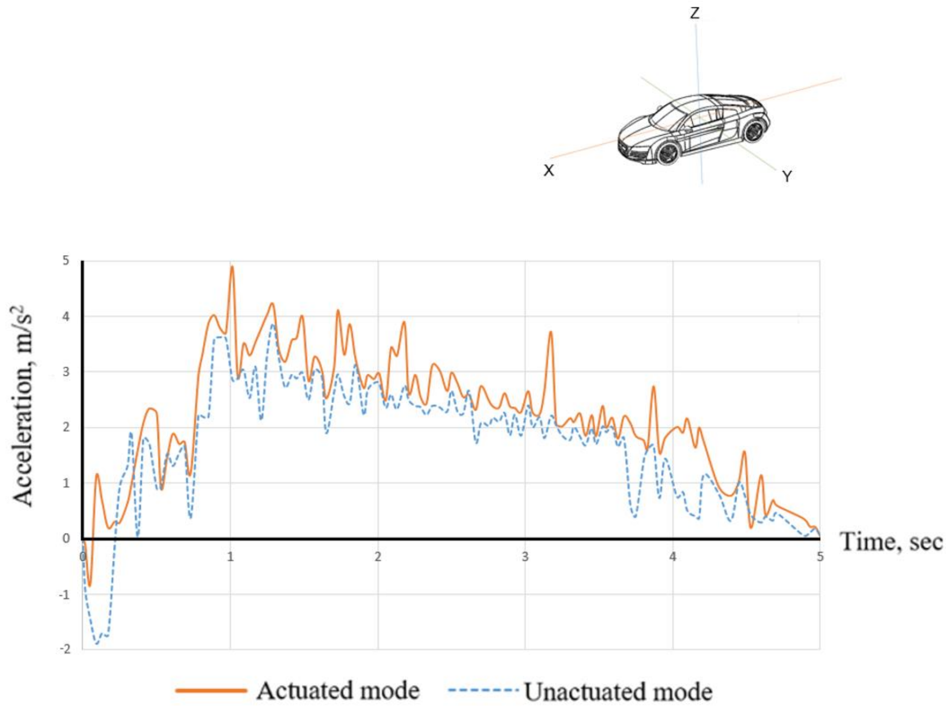
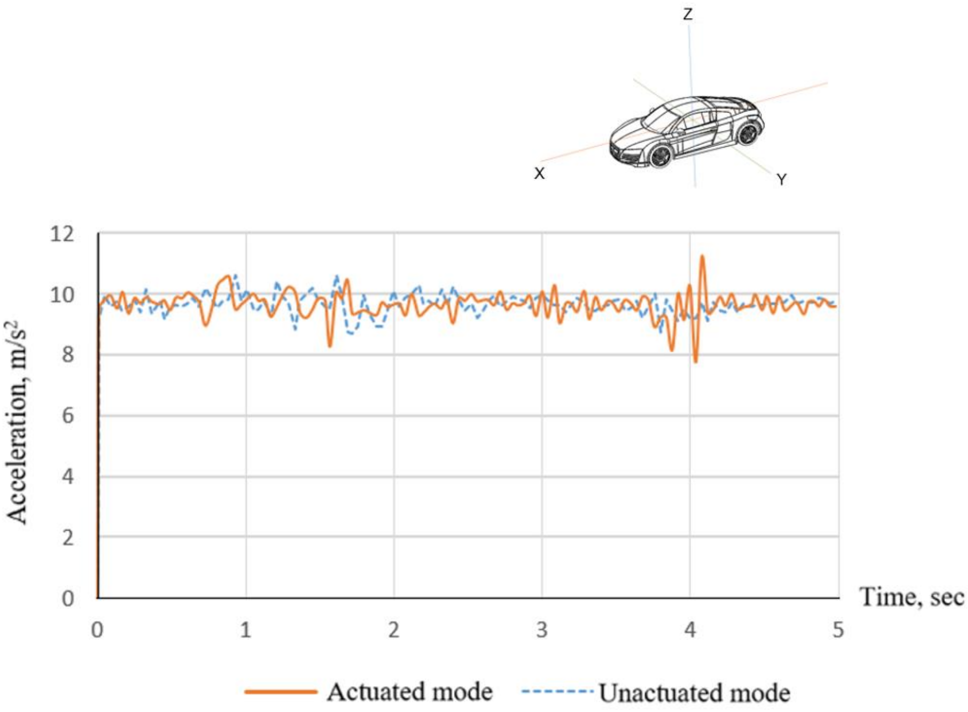


Figure 20. Vehicle axis coordinate systems: longitudinal axis (x-axis), transverse axis (y-axis), vertical axis (z-axis)


Z
X
Y
Acceleration, m/s²
Time, sec
5
4
3
2
1
0
-1
-2
0
1
2
3
4
5
Actuated mode
Unactuated mode

(a)



(b)

Figure 21. (a) Longitudinal acceleration (x-axis) and (b) vertical acceleration (z-axis) signals

Chapter 6. Conclusion

In the proposed work, the SMA based SSC actuator was designed and fabricated. In addition, the air flow separator was manufactured and installed into the small-size car.

Bending deformation performance of the SSC actuator was evaluated by fixing the sample to a support, with heating the actuator using electric current and cooling at room temperature.

For performance evaluation of the flow separator, the field test was conducted and the results were obtained for longitudinal acceleration and vertical acceleration in two modes: with actuation of the actuator and without actuation.

The presented smart material based actuator and the soft air flow separator mechanism can be applied to the development of the morphing car.

Bibliography

[1] A. AbuZaiter, E.L. Ng, S. Kazi, and M.S. Mohamed Ali, 2015, “Development of Miniature Stewart Platform Using TiNiCu Shape-Memory-Alloy Actuator”, Advances in Materials Science and Engineering, Vol. 2015.

[2] A. Lu, D. Grant, and V. Hayward, 1997, “Design and comparison of high strain shape memory alloy actuators”, Proceeding of the IEEE International Conference on Robotics and Automation, Vol.1, pp. 260-267.

[3] H. Rodrigue, W. Wang, M.-W. Han, Y.-J. Quan, and S.-H. Ahn, 2015, “Comparison of mold designs for SMA-based twisting soft actuator”, Sensors and Actuators A 237 (2016), pp. 96-106.

[4] H. Rodrigue, W. Wang, B. Bhandari, M.-W. Han, and S.-H. Ahn, 2014, “Cross-Shaped Twisting Structure Using SMA-Based Smart Soft Composite”, International Journal of Precision Engineering and Manufacturing Technology, Vol. 1, No. 2, pp. 153-156.

[5] H. Rodrigue, W. Wang, B. Bhandari, and S.-H. Ahn, 2015, “Fabrication of wrist-like SMA-based actuator by double smart soft composite casting”, Smart Materials and Structures, 24 (2015).

[6] H. Rodrigue, W. Wang, B. Bhandari, M.-W. Han, and S.-H. Ahn, 2015, “SMA-based smart soft composite structure capable of multiple modes of actuation”, Composites Part B, 82 (2015), pp. 152-158.

[8] M.-W. Han, H. Rodrigue, S. Cho, S.-H. Song, W. Wang, W.-S. Chu, and S.-H. Ahn, 2015, “Woven type smart soft composite for soft

morphing car spoiler", Composites Part B 86 (2016), pp. 285-298.

[9] A.R. Norwazan, A.J. Khalid, A.K. Zulkiffli, O.Nadia and M.N. Fuad, 2012, "Experimantal and numerical analysis of lift and drag force of sedan car spoiler", Applied Mechanics and Materials, Vol. 165 (2012), pp. 43-47.

[10] J. Huang, X. Chen, and L. Zhong, 2013, "Analysis and testing of MR shear transmission driven by SMA spring", Advances in Materials Science and Engineering, Vol. 2013.

[11] L. Meisner, A. Lotkov, Y.Mironov, and A. Neyman, 2010, "" Evolution of structural-phase states in TiNi surface layers synthesized by electron beam treatment", Journal of Nanotechnology, Vol. 2010.

[12] X. Zhang, W. Toet, J. Zerihan, 2006, "Ground effect aerodynamics of race cars", Applied Mechanics Review, Vol. 59, pp. 33-49.

[13] C.-H. Tsai, L.-M. Fu, C.-H. Tai, Y.-L. Huang, J.-C. Leong, 2009, "Computational aero-acoustic analysis of a passenger car with a rear spoiler", Applied Mathematical Modelling 33 (2009), pp. 3661–3673.

[14] E. Guilmineau, 2008, "Computational study of flow around a simplified car body", Journal of Wind Engineering and Industrial Aerodynamics 96 (2008), pp. 1207–1217.

[15] P. Padagannavar, and M. Bheemanna, 2016, "Automotive computational fluid dynamics simulation of a car using ANSYS",

International Journal of Mechanical Engineering and Technology (IJMET), Vol. 7, Issue 2, March-April 2016, pp. 91–104.

[16] M.H. Djavareshkian, and A. Esmaeli, 2011, “Optimization of Smart Spoiler for Race Car”, International Conference on Fluid Dynamics and Thermodynamics, Dubai, January 25-27, 2011.

[17] C. Othmer, 2014, “Adjoint methods for car aerodynamics”, Journal of Mathematics in Industry 2014, 4:6.

[18] C. Thill, J. Etches, I. Bond, K. Potter, and P. Weaver, 2008, “Morphing skins”, The Aeronautical Journal.

[19] S. Seelecke, and I. Muller, 2004, “Shape memory alloy actuators in smart structures: modeling and simulation”, Applied Mechanics Reviews, Vol. 57, pp. 23-46.

[20] J.W. Sohn, Y.M. Han, S.B. Choi, Y.S. Lee, and M.S. Han, 2009, “Vibration and position tracking control of a flexible beam using SMA wire actuators”, Journal of Vibration and Control, 15(2), pp. 263–281.

[21] W.-H. Hucho, “Aerodynamics of Road Vehicles: from fluid mechanics to vehicle engineering 1st ed.”, Imprint: Butterworth-Heinemann, 1987.

[22] B.Agathangelou, and M. Gascoyne, 1998, “Aerodynamic Design Considerations of a Formula 1 Racing Car," SAE Technical Paper 980399.

[23] J. Katz, 2006, “Aerodynamics of Race Cars”, Annual Review of Fluid Mechanics, Vol.38, 2006, pp. 27-63.

[24] M.A. Passmore, S. Richardson, and A. Imam, 2001, “An

Experimental Study of Unsteady Vehicle Aerodynamics”, The Proceedings of the Institution of Mechanical Engineers, Vol 215 Part D, pp.779-788.

[25] J. Zerihan, and X. Zhang, 2000, “Aerodynamics of a Single Element Wing in Ground Effect”, Journal of Aircraft, Vol.37, No. 6, pp. 1058-1064.

초록

자동차용 소프트 모핑 유동박리장치의 제조 및 평가

항공, 자동차 산업에서의 변형기술에 대한 관심은 지난 수십년 동안 증가했다. 그러한 기술들은 다양한 방면에서 자동차의 성능 및 효율을 높이는데 기여할 것으로 예상되었다. 특히, 자동차의 변형 구조는 원래 사용하던 자동차 표면의 열린 틈과 나뉘어진 부분들을 대체하여 좋은 특성을 가질 수 있게 하는데, 원래의 자동차 표면들은 공기역학적인 손해를 비롯해 소음 진동등의 안 좋은 특성들을 가지게 한다. 이번에 제안된 연구를 통해 형상기억합금(SMA)로 이루어진 1/8 비율의 RC 자동차의 뒷면에 장착되어 공기분리기 역할을 하는 지능유연복합 구동기 제작 공정이 개발되었다. 공기 역학적 성능과 효율을 평가하기 위해 주행 시험을 하였고, 그 결과는 같은 조건에서 공기분리기가 없는 자동차의 성능과 비교하여 평가하였다.

Keywords: 지능형 재료, 형상기억합금, 지능형 연성 복합재, 모핑구조, 자동차용 유동박리장치

***학번**: 2015-23294*